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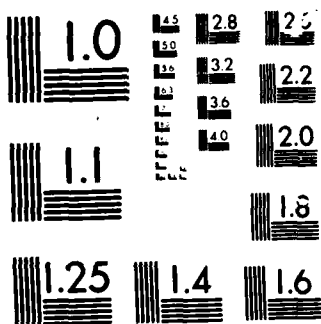   CA M R PAULSON 01 FEB 86 NOSC/TD-867

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LIDAR MEASUREMENTS INDICATING ATMOSPHERIC INHOMOGENEITIES

Merle R. Paulson

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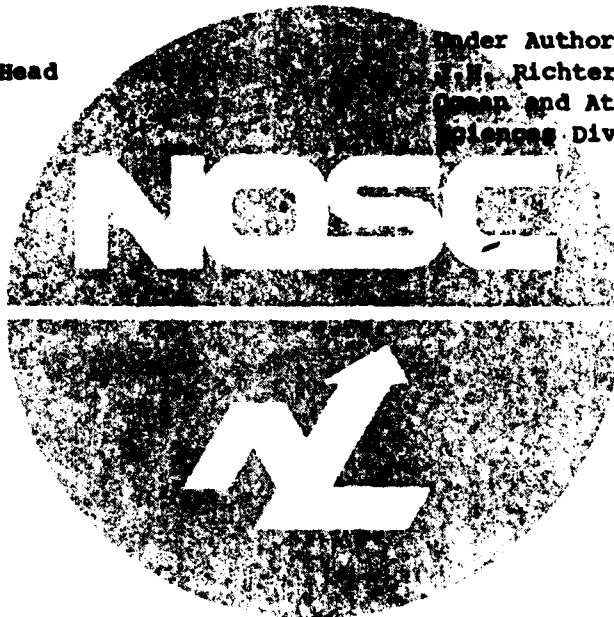
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Various methods for interpreting lidar data require that the atmospheric aerosol distributions be homogeneous in the horizontal direction. While many workers in aerosol extinction and lidar backscatter report that rarely, if ever, is the atmosphere sufficiently homogeneous horizontally for this to be a good assumption, most of them make the assumption anyway, or select cases where they say that, for their purposes, it is sufficiently homogeneous horizontally.

This document considers some of the findings reported in the literature and presents some examples of lidar data obtained off the bluff at Point Loma in San Diego, California, showing pronounced aerosol inhomogeneities in the horizontal.

It is concluded that while the lidar may be useful for studying atmospheric aerosols when used in conjunction with other meteorological measurements, it probably cannot be used as a stand-alone device for determining visibility.

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INTRODUCTION

The use of the lidar as a tool in the investigation of characteristics of the atmosphere has become very popular in recent years. It has been used to study everything from atmospheric pollutants (Schuster and Kyle, 1980, and Uthe, 1981) to the investigation of winds and wind profiles in the boundary layer (Eberhard and Schotland, 1980, and Sroga et al., 1980).

Lidars have also been used to try to determine visibility through the atmosphere (Lentz, 1982). If successful, this would be a very useful method for determining real-time visibilities on board ships at sea. There are, however, some difficulties associated with the use of lidars for this purpose.

The purpose of this report is to review some of the ways lidar data have been used to try to determine visibility and to show some data for lidar firings made from Point Loma in San Diego, California, that indicate atmospheric inhomogeneities.

METHODS OF DETERMINING VISIBILITY FROM LIDAR RETURNS

Three methods of determining visibility from lidar returns are considered here. They all use the logarithmic range-adjusted power, defined as

$$S(R)=Ln[P(R)*R^2] \qquad (1)$$

where P(R) is the power returned from range R.

SLOPE METHOD

In probably the simplest method of determining visibility, values of S(R) are plotted as a function of range. If the atmospheric conditions are homogeneous along the propagation path, this results in a straight line and the slope of this line is equal to two times the extinction coefficient. This extinction coefficient is then used to calculate the visibility.

This requirement that the atmosphere be homogeneous along the propagation path rarely occurs.

Kohl (1978) says that to avoid errors associated with atmospheric inhomogeneity, many users of the slope method have picked distance intervals for calculating the average attenuation coefficient in which the slope of S(R) is negative and the deviation from a straight-line fit is small. Such properties are taken to be indications of homogeneity in those intervals. He says, however, that more than this is needed to ascertain homogeneity. Kohl also says that the problem encountered in any single-wavelength lidar technique is that there is generally an infinite number of dispersion configurations that will give a return signal of any specified shape.

LIDAR INVERSION ALGORITHM METHOD

A second method used to try to determine extinction, and from it visibility, assumes that the ratio of backscatter to extinction along the propagation path is constant. The S(R) curve as a function of range is then inverted to get a curve of extinction as a function of range. This requires that not

only must the ratio of backscatter to extinction be constant, but it also must be accurately known.

Klett (1981) has developed a "stable" analytical inversion solution for processing lidar returns. He assumes that the backscatter-to-extinction ratio along the propagation path is constant and of the form

$$\beta = c_2 (\sigma)^k \tag{2}$$

where β is the backscatter coefficient, σ is the extinction coefficient, and c_2 and k are constants. He then gets the following equation:

$$\sigma(R) = \frac{\exp[(S-S_m)/k]}{\left\{ \sigma_m^{-1} + \frac{2}{k} \int_R^{R_m} \exp[(S-S_m)/k] dR \right\}} \tag{3}$$

where $S_m = S(R_m)$, $\sigma_m = \sigma(R_m)$, and R_m is a reference range such that a solution is generated for $R \leq R_m$.

This solution has the limitations of the assumption made in equation (2). Even if equation (2) were applicable, a correct interpretation of atmospheric extinction structure deduced from lidar data in this manner would require precise knowledge of the value of c_2 (Hughes et al., 1985). Furthermore, this constant cannot vary along the propagation path.

Kneizys et al. (1983) show that when the relative humidity is not constant along the propagation path, the value of c_2 is not constant either. While some mean value of c_2 can be used that will give a zero error in the integrated extinction along a given propagation path over a given distance, an incorrect value can result in a very large error under some conditions (Paulson, 1985). The value of c_2 for zero error will also change if the propagation distance is changed.

Klett (1985) later modified his lidar inversion algorithm to try to allow for variations in the backscatter-to-extinction ratios. He does this by determining a log-gaussian fit of backscatter-to-extinction ratio versus extinction for some data taken at Meppen, Germany. These data consist of nine data pairs. It is not explained how these data were obtained, but it appears that they may be the result of extensive data averaging. Even if this is not the case, the data are from one location and are subject to limited conditions. Mulders (1984) shows an example of good correlation between extinction and backscatter for one day, but when data for a month were considered he obtained a plot that shows no correlation at all, so fitting a curve to one set of data does not appear to be too useful.

These inversion methods also require that a value of extinction coefficient be known, or assumed, for a reference range, R_m. So, although the inversions provide a stable solution, the solution can still be very much in error.

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MULTIPLE ZENITH ANGLE METHOD

The third method of obtaining visibility from lidar data makes use of multiple zenith angle lidar measurements to try to determine vertical extinction profiles. While this technique allows variation of atmospheric conditions in the vertical, it requires horizontal homogeneity at any given altitude.

Spinhirne et al. (1980) report that because of atmospheric inhomogeneity, a direct solution of the multi-angle measurements at individual height levels was not found to be feasible. They then employed a layer-integrated form of the angle-dependent lidar equation. This required that they assume that the aerosol extinction-to-backscatter ratio was constant within a defined layer and that the vertical transmission through the layer was the same for all slant paths. Something, it appears, that they had found to be not true.

Russell and Livingston (1984) also used the multiple zenith angle method. They say that, in practice, the slant lidar technique encounters difficulties because of the need for high accuracy in measuring relative transmitted energy and the lidar backscattered signal, and because of the horizontal and temporal inhomogeneity of the atmosphere. They say that within the convectively formed boundary layer, rarely if ever does the backscatter coefficient have the degree of horizontal homogeneity required.

Kunz (1983) assumes horizontal homogeneity in the lower atmosphere. He says that this has been proved to be valid in most cases in the absence of local aerosol sources, excluding cases of extremely low visibility, where patches of fog might occur. What is considered extremely low visibility is not stated.

LIDAR MEASUREMENTS AND S(R) CURVES

While all the lidar methods discussed require either that atmospheric aerosols be homogeneous horizontally or that the ratio of backscatter to extinction be accurately known along the propagation path, these conditions probably do not exist in situations of most interest to the Navy. It is when visibilities are low that the Navy has the greatest requirements for accurate measurements of visibility.

The Naval Ocean Systems Center has made many horizontal lidar measurements out over the ocean from the bluff at Point Loma in San Diego, California. The elevation of the site is about 40 m above the ocean surface.

A description of some of these measurements and a few S(R) curves are presented here.

DESCRIPTION OF EQUIPMENT AND MEASUREMENT TECHNIQUE

Two visioceilometer lidars were used to make the visibility measurements. They output a 6 ns pulse of about 13 mJ at 1.06 μm into a 1 mrad beamwidth. The receiver has a 3-mrad field of view. More details can be found in Lentz (1982).

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The two lidars were mounted about 15 cm apart on a metal plate. This plate was fastened to a tripod which could be adjusted in azimuth and elevation. Each lidar was adjusted so that the crosshairs in the viewfinder were lined up on the mast of a sailboat about 5 or 6 km away. The aim of the two lidars could then be controlled by the tripod adjustments, while the two propagation paths remained essentially parallel. The data were recorded on a Memodyne digital recorder for later processing. The lidars were aimed horizontally out over the ocean and fired about once per minute.

DISCUSSION OF DATA

Figure 1 shows an example of the raw data curves for each lidar and compares each curve to the corresponding curve when the laser output was covered.

The raw data samples were processed to remove the system and background noise. These data were then modified by equipment calibration terms and corrected for range dependence to get plots of S(R) data as a function of range.

Figure 2 shows two examples of S(R) versus range curves for lidar #025090 taken at 0711 and 0718 PDT on 27 August 1985. Figure 3 shows the same thing for lidar #025091 for 0734 and 0735 PDT on 27 August 1985. Visibility was approximately 10 km when these data were taken. The times are different for the two lidars since only one recorder was available during these measurements.

These curves show considerable structure, indicating that atmospheric conditions were not horizontally homogeneous. If conditions were homogeneous, the results should have been straight lines with some negative slope, which depends on the aerosol extinction.

The two lidars were also fired nearly simultaneously along the same propagation path. This provided an opportunity to compare the returns for the two. In these cases (Figure 4) two recorders were available.

The two lidars were pointed horizontally out to sea. First, one lidar was fired, then within 1 or 2 seconds, the second lidar was fired. Figure 4 shows examples of these firings, which were conducted on 10 and 11 April 1985. In these tests, visibility was about 10 to 15 km. Horizontal inhomogeneity is also seen in these plots.

The two graphs in Figure 4a show good agreement between the two lidars out to almost 1 km. The signal-to-noise ratio was probably not too good beyond that range. These two graphs also show how quickly conditions can change. The upper graph was taken at 0901 PST and the lower one at 0903 PST, yet the curves are quite different.

The graphs in Figure 4b were taken on the same day, but a little more than an hour later. These also show quite good agreement between the lidars out to about 1 km, or a little more. The lower graph is for data taken 1 minute later than the data in the upper graph.

Figure 4c compares S(R) curves for the two lidars for data taken at 0805 and 0810 PST on 11 April 1985. While these curves show some small differences between the two lidars, the overall agreement is quite good.
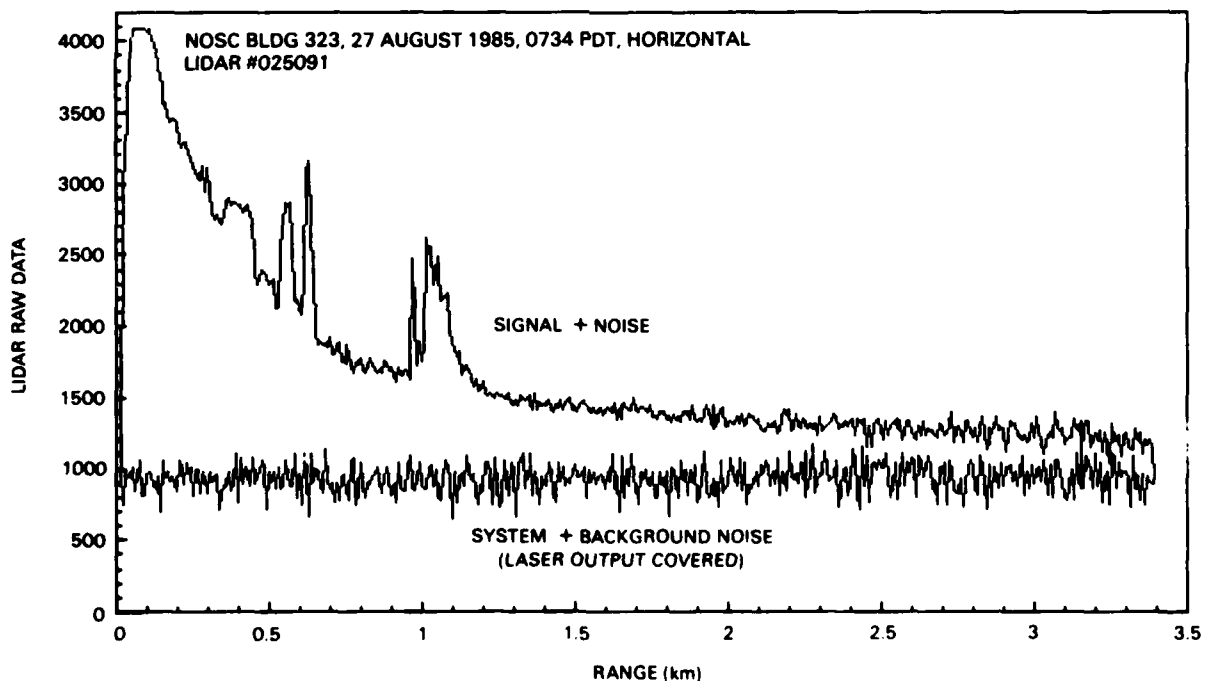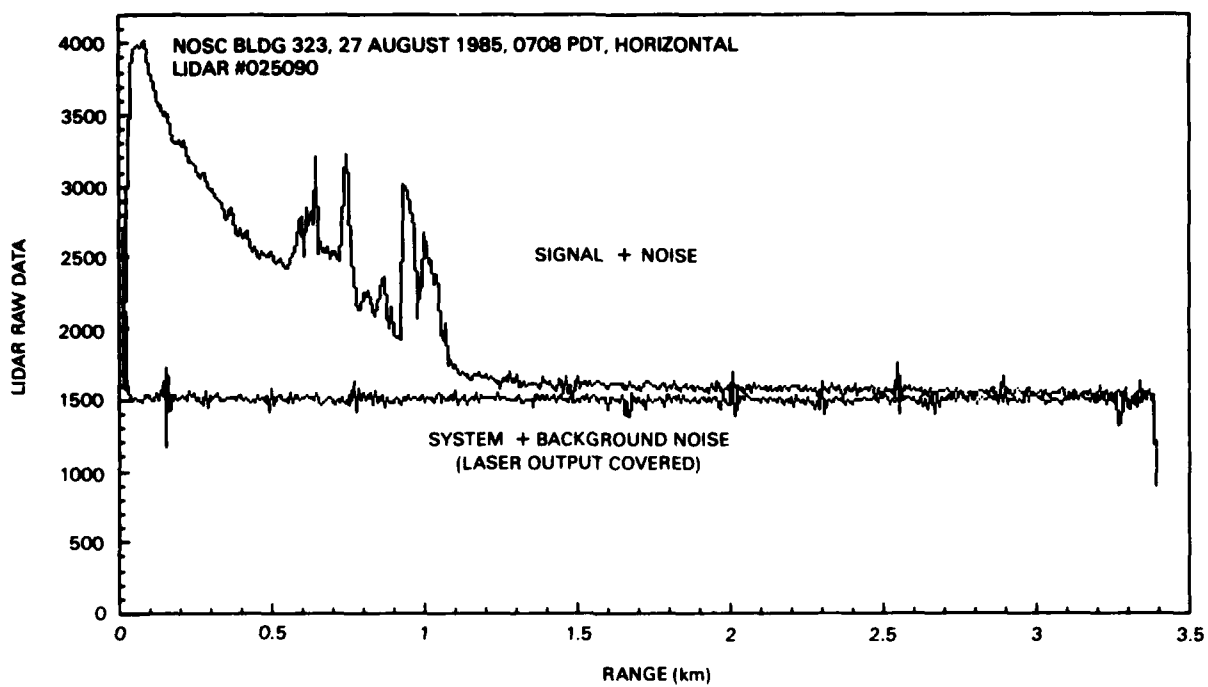
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Figure 1. Comparisons of raw data plots for normal operation of the lidars and plots made when the laser outputs were covered. Visibility was about 10 km.
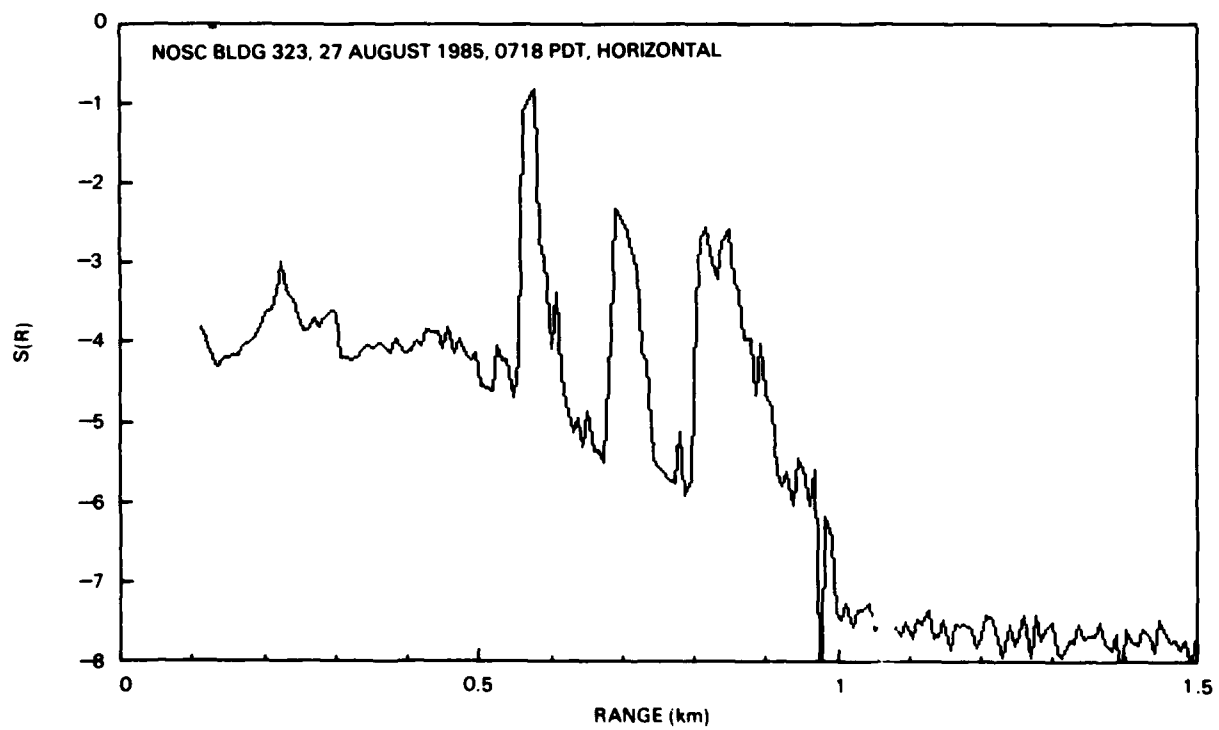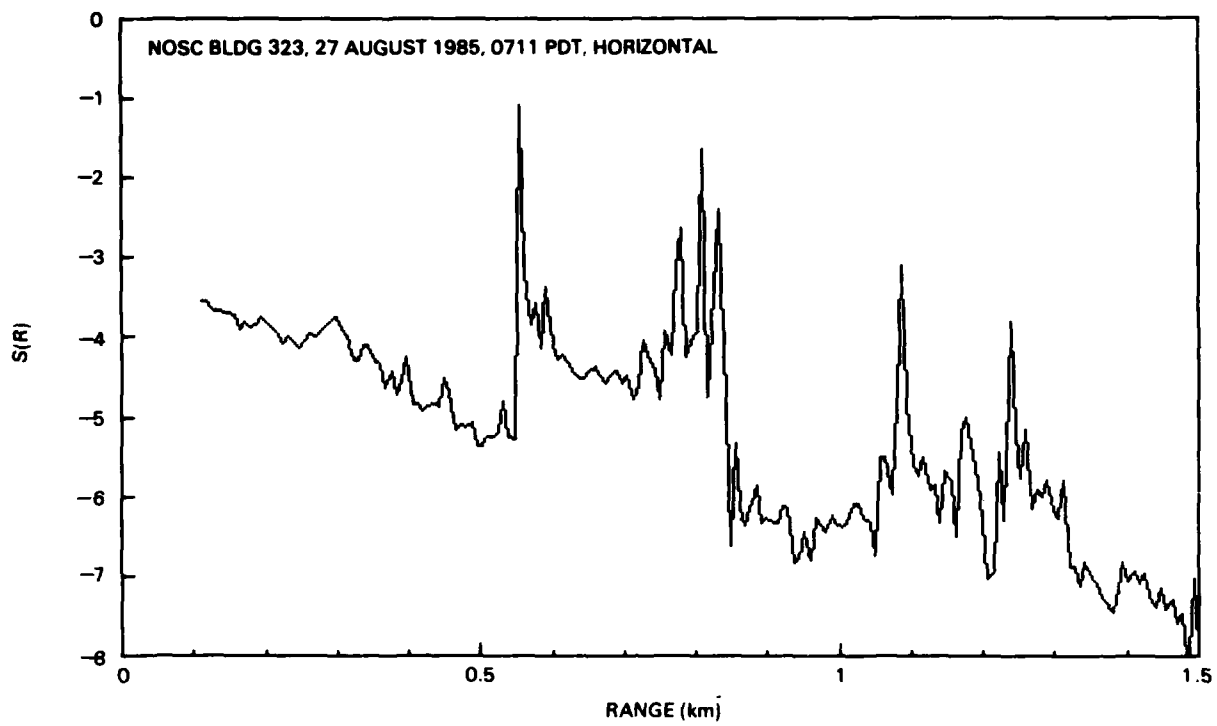
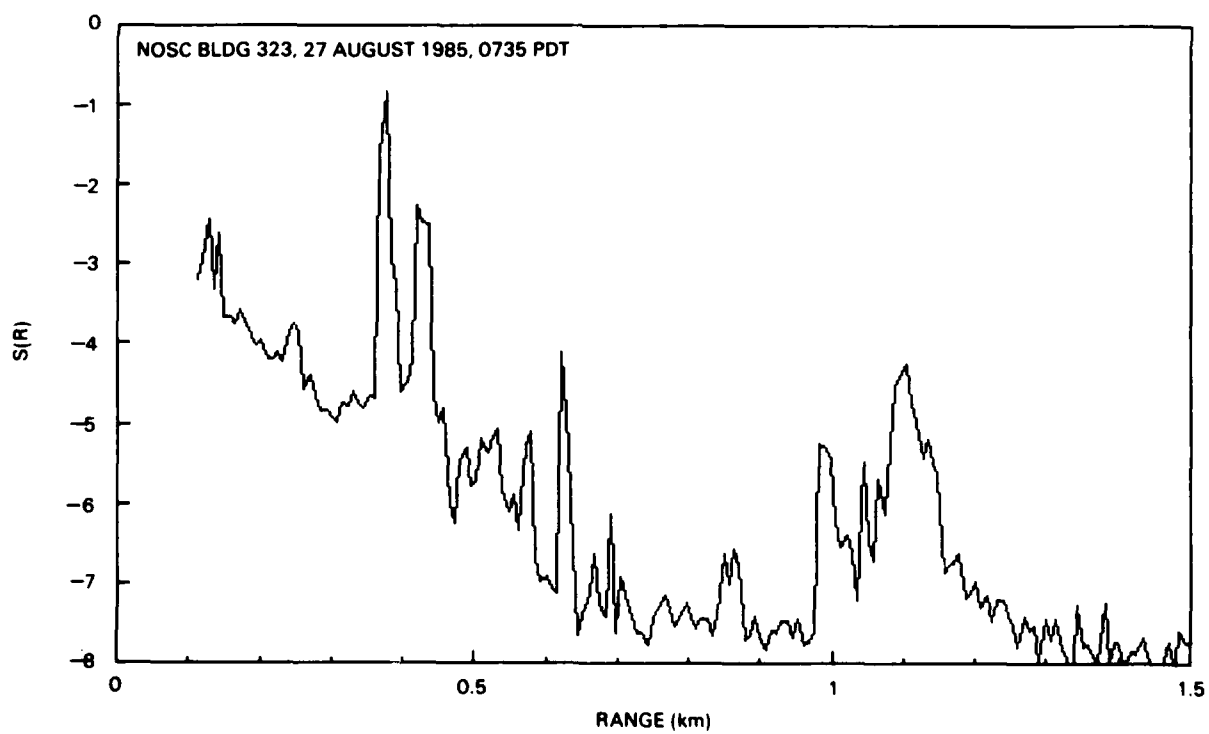Figure 2. S(R) data plotted as a function of range for lidar #025090. Visibility was about 10 km.
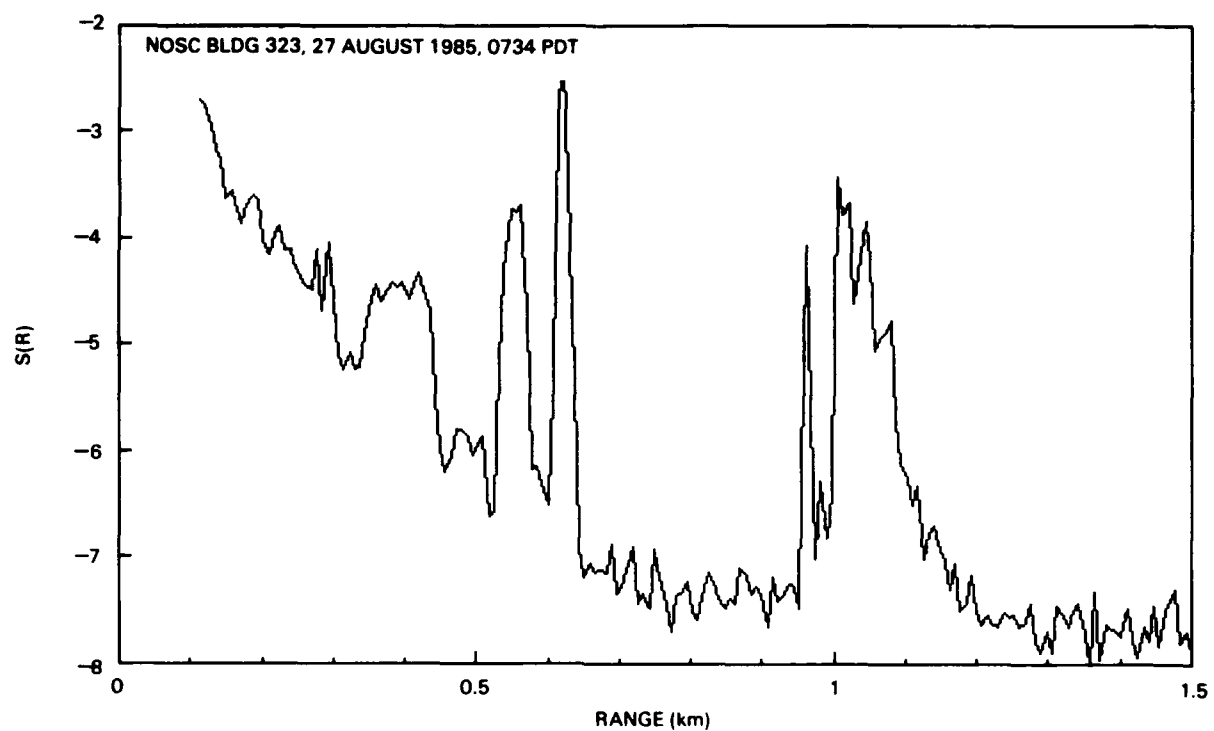
Figure 3. S(R) data plotted as a function of range for lidar #025091. Visibility was about 10 km.
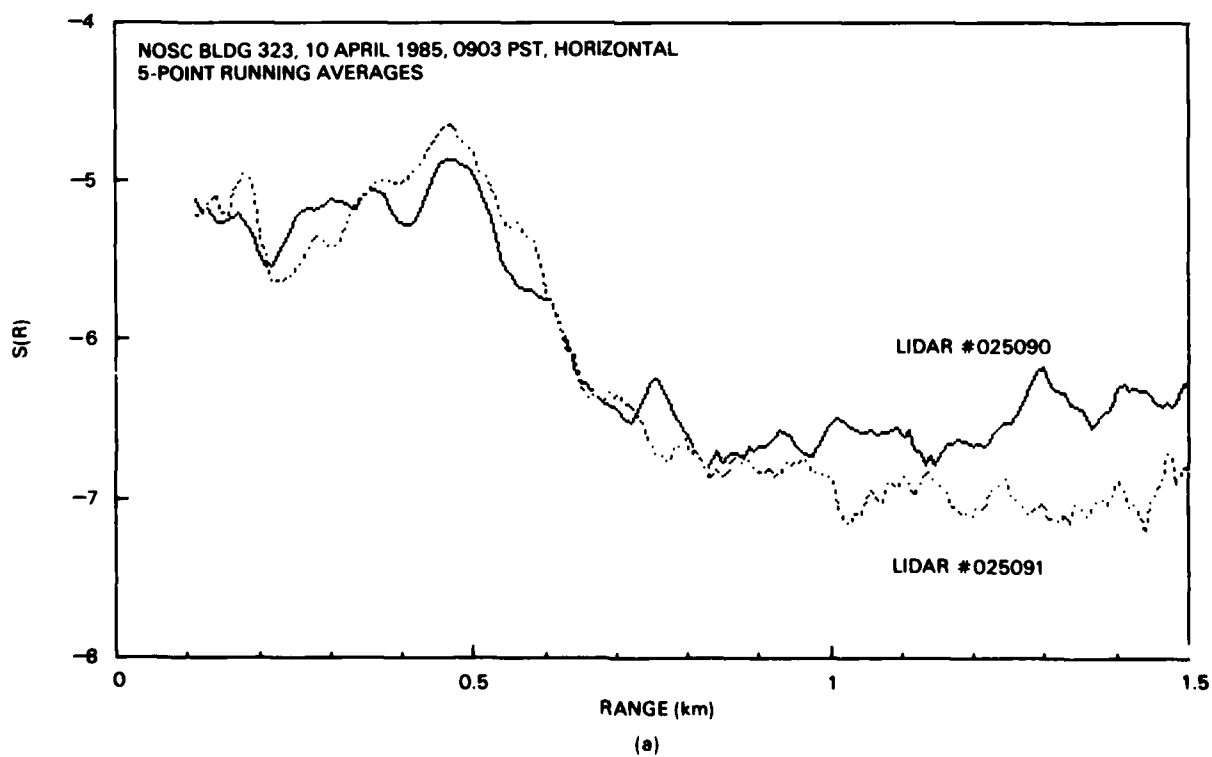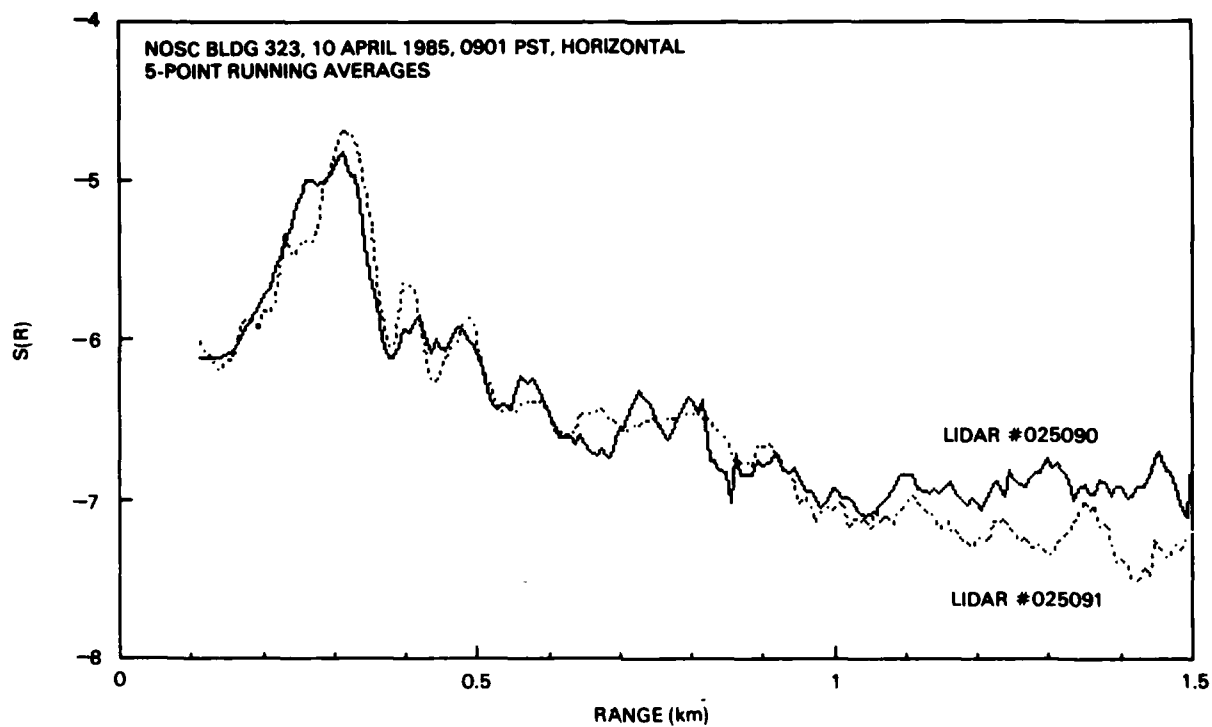
Figure 4. Comparison of S(R) data plotted as a function of range for the two lidars over the same propagation path. The two lidars were fired within 1 to 2 seconds of each other.
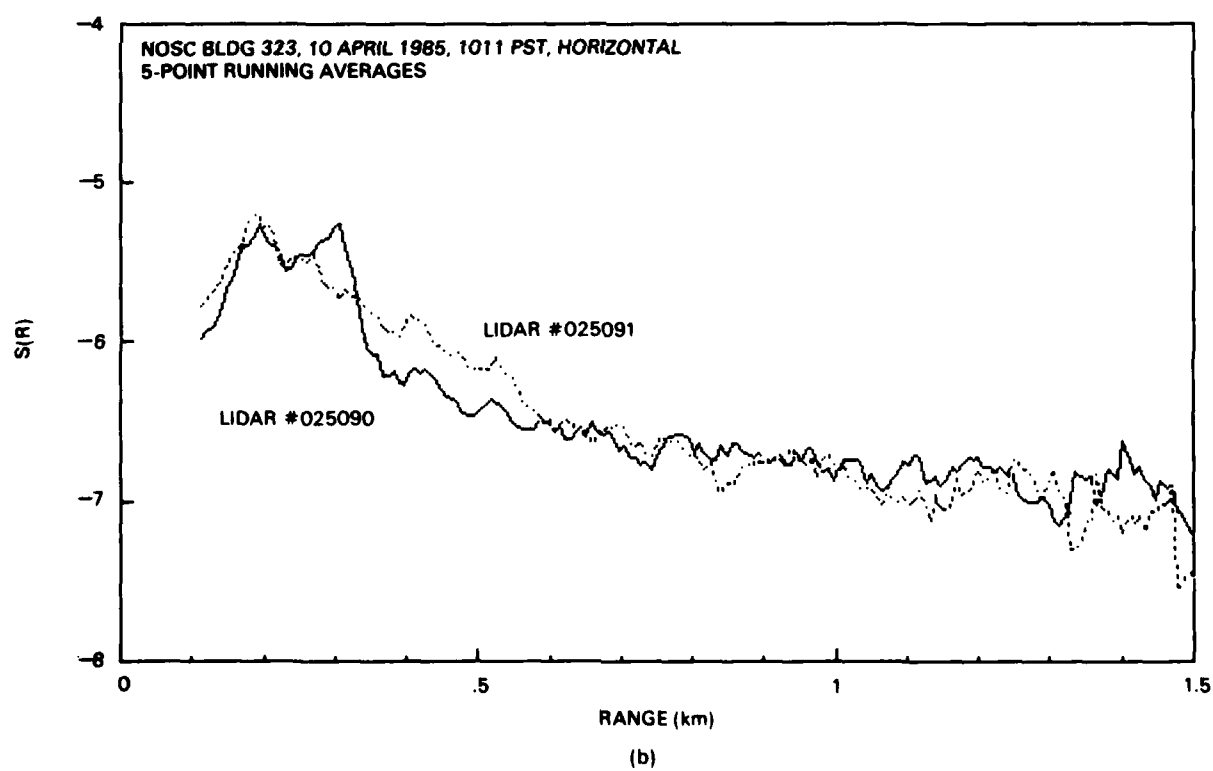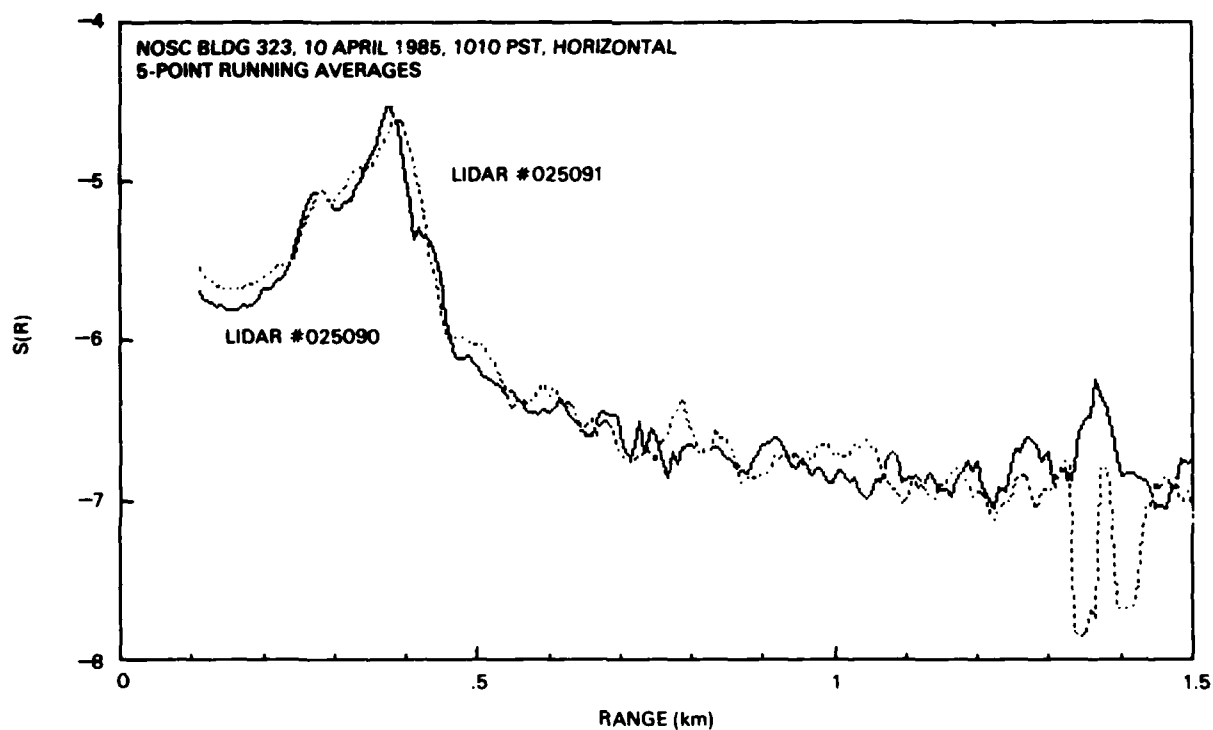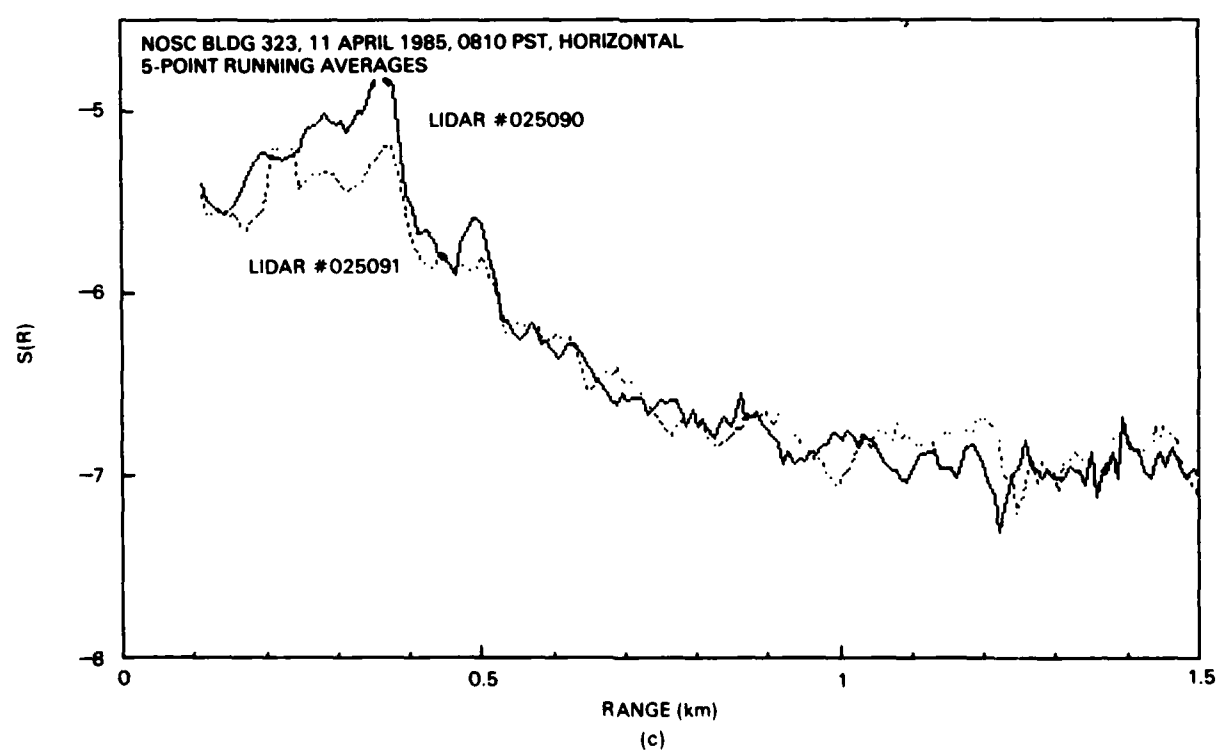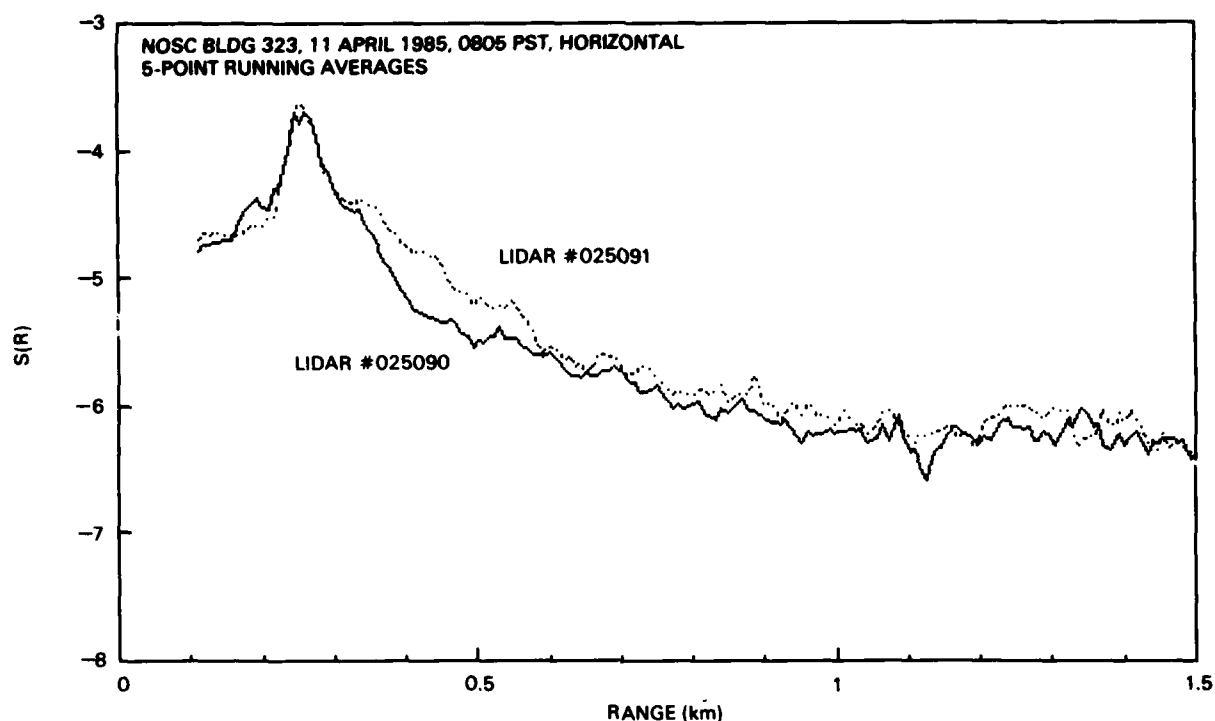
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Figure 4. (Continued).

Figure 4. (Continued).

SUMMARY AND CONCLUSIONS

Many S(R) plots as a function of range have been made for horizontal lidar shots, taken at various times, out over the ocean from the bluff at Point Loma in San Diego, California. Frequently these plots show quite pronounced structure, indicating the presence of horizontal inhomogeneity in the atmospheric aerosols. Ten examples of this have been shown here.

When the two lidars are fired along the same path at nearly the same time, their S(R) curves show good agreement, indicating that the structure observed is caused by aerosol inhomogeneities and not by problems with the instruments.

Although these results are for only one site, other people working with lidars have reported that the atmosphere is rarely, if ever, sufficiently homogeneous horizontally for such methods as the multiple zenith angle technique to be used to determine visibility. This would apply to the slope method as well.

Lidar inversion techniques require that the backscatter-to-extinction ratio be constant along the propagation path and that it be accurately known. Neither of these requirements is, or can be, met in most operating conditions.

Although the lidar may have some use as a research tool, when used in conjunction with other meteorological instruments, its use as a stand-alone tool for routinely determining visibilities does not appear feasible. While the user will probably always get an answer, the answer could frequently be greatly in error. To rely on such an answer might be very dangerous at times.

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